AFCRL #670

RULING OF LARGE DIFFRACTION GRATINGS UNDER INTERFEROMETRIC CONTROL

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Spectroscopy Laboratory
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Final Report
Contract AF19(604)-1965
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DIV. 7

The work summarized in this final report and in the eighteen Quarterly Status Reports which have been submitted on this project between December 31, 1956 and March 31, 1961, has been reported in the following relevant publications:

RULING OF LARGE DIFFRACTION GRATINGS WITH INTERFEROMETRIC CONTROL, by George R. Harrison, Neville Sturgis, Stanley C. Baker, and George W. Stroke, JOSA, Vol. 47, No. 1, pp. 15-22, January 1957.

PHOTOELECTRIC FRINGE SIGNAL INFORMATION AND RANGE IN INTERFEROMETERS WITH MOVING MIRRORS, by George W. Stroke, JOSA, Vol. 47, No. 12, pp. 1097-1103, December 1957.

THE CONTROLLED RULING OF DIFFRACTION GRATINGS, by George R. Harrison, Proceedings American Philosophical Society, Vol. 102, No. 5, pp. 483-491, October 20, 1958.

INTERFEROMETRICALLY CONTROLLED RULING OF 10-INCH DIFFRACTION GRATINGS, by George R. Harrison, Neville Sturgis, Sumner P. Davis, and Yahiko Yamada, JOSA, Vol. 49, No. 3, pp. 205-211, March 1959.

THE ATTAINMENT OF HIGH RESOLUTION WITH DIFFRACTION GRATINGS AND ECHELLES, by George R. Harrison and George W. Stroke, JOSA, Vol. 50, No. 12, pp. 1153-1158, December 1960.

Other relevant contracts:

Office of Ordnance Research
Contract DA19-020-ORD-1887
June 15, 1952 to June 15, 1956

National Science Foundation
Grant NSF G-1989
September 26, 1955 to September 26, 1957

Relevant papers on which this work depends are:

G. R. Harrison, JOSA, 39, 6, 413, 1949
G. R. Harrison and J. E. Archer, JOSA, 41, 8, 495, 1951
G. R. Harrison and G. W. Stroke, JOSA, 45, 2, 112, 1955

OBJECTIVES

The purpose of this project was to increase the quality and availability of diffraction gratings of the most useful types, and to develop new techniques which would make possible the production of gratings having higher resolving power, dispersion, speed, and usefulness than those previously available.

Diffraction grating spectrographs are of increasing importance in all fields of science. Within only a few years the total number of new gratings used each year in the United States has grown from a few to many hundreds. Larger, faster, more powerful, and cheaper gratings are needed for space-research programs, for modern astronomy, for analytical procedures in chemical and metallurgical laboratories, and in the continuing work of the physicist and chemist in determining the structures of atoms and molecules.

The gratings developed in the program here described have been designed principally for use in the visible and ultraviolet regions of the spectrum, although important applications in the infrared and far ultraviolet can be expected to result from the project.

When this contract was initiated we had succeeded at M.I.T. in ruling 8-inch plane gratings which approached in resolution, and exceeded in other qualities, any gratings ruled up to that time. We have now ruled plane gratings up to 10-inches in width, with resolution much higher than any previously available, and with much weaker satellite and ghost defects. A number of master gratings have been produced from which replicas have been produced commercially, and the demand for gratings from M.I.T. ruled masters now far exceeds the supply.

At least six ruling engines utilizing interferometric control, as developed for this project, are now under construction in various parts of the world, and the availability of gratings of ultra-precision can be expected to improve as a result of the application of the principles here developed.

The initial objectives of the project have been realized, and much experience has been obtained which is being used to carry the project further, notably in the construction of a new interferometrically controlled ruling engine for the production of gratings up to 18 inches in ruled width and ten inches in groove length.

THE RULING ENGINE

The basic mechanical parts of the engine, which were presented to M.I.T. by the University of Chicago in 1948 in a form about two-thirds finished, were modifications of a ruling machine, the design of which was begun under the direction of Dr. A. A. Michaelson in 1900. It had been modified under the direction of Dean H. G. Gale, F. Pearson, and P. G. O'Donnell, and others in the 1930's. Over the years various parts of the engine, including the screw, had warped, and it was not suitable for the production of even inferior gratings. We felt, however, that it would serve as an excellent test instrument for a method of interferometric control which might be developed. In the years following 1949 the engine was completed and modified mechanically, and servo-controls were applied to it, using interferometers to locate at all times its crucial moving parts, and servo-motors to correct inadequacies in their motion.

The engine when uncontrolled produces errors in ruling which are some 400 times the magnitude of the maximum that could be tolerated in a precision grating. The servo-controls keep in synchronism the motion of the diamond ruling the groove, and the advance of the grating carriage, at the same time introducing appropriate corrections for atmospheric pressure variations, which change the effective control wavelength. Despite such interferometric monitoring the engine for some years

showed serious residual errors, which were found to result in large part from micro-rotations of the blank carriage about a vertical axis as it slowly proceeds along its ways.

A second interferometer system to give control of the plate carriage rotation was than installed. A number of excellent plane gratings, up to 8 inches in ruled width, had thus been produced on the engine when the present contract began.

The last of the series of some 70 earlier test gratings had been found to approach in quality the best yet ruled on any engine, showing resolving powers exceeding 600,000 in the green, and giving crisp spectral lines with low local background even at angles up to 63° in autocollimation. The Rowland ghost intensities were lower than any previously reported, ranging from 1/700 to 1/800 at 75°, corresponding to 1/25,000 to 1/29,000 in the first order of a 15,000 groove-per-inch grating.

At the conclusion of the present contract extremely bright 10-inch gratings have been produced which can be used effectively at very high angles (12th order green at 7500 grooves per inch.) Nearly a dozen large plane gratings of high quality have now been produced on the engine, which show resolving powers closely approaching the theoretical 900,000 in the 12th order green and above 1,200,000 in the 26th order of 2537 A. To get full usefulness of this power the gratings are tested in a 40-foot spectrograph having 10-inch concave mirrors.

Rowland ghosts in several of the gratings were found to be well below 1/10th per cent in the 12th order green, and below 1 part in 100,000 at the angles in which ghost intensities are usually measured for purposes of comparison. Thus in these gratings Rowland ghosts are sensibly absent for wavelengths above 2000 A.

As in all large diffraction gratings, the residual errors are mainly such as to produce satellites. These have been systematically reduced over the five years the contract has been in force. In the better gratings all satellite intensities total well under 1%, with no single satellite stronger than 0.3%.

The stronger satellites found in our previous 8-inch gratings were found to originate from tilting of the interferometer mirrors and rotation about a horizontal axis of the blank while being ruled.

Since these large gratings have 50 square inches of ruled area, and are well blazed, they are extremely fast, 20 seconds being adequate to give satisfactory exposures to ordinary sources at dispersions as high as 12 mm per angstrom. Some of the gratings concentrate more than 50% of incident green light in a single high order.

GRATING QUALITY AS REPORTED BY USERS

That the gratings produced in this program are of the high quality our tests indicate is substantiated by reports from various users, and by the demand for replicas made from them by such firms as Bausch & Lomb, Inc., and Jarrell-Ash Co. It has been our policy to furnish gratings for use as masters to firms regularly engaged in the sale of gratings, which possess the techniques needed for producing replicas of quality approaching that of the master grating. Inquiries have been received from a number of companies interested in gratings, and their needs will be met as far as possible, bearing in mind that the chief purpose of the project is improvement in techniques rather than production of gratings.

Professor John Strong, a ruler of excellent gratings, who has long been in charge of the ruling engine program at Johns Hopkins University, where the modern ruling engine was first developed by Professor H. A. Rowlands, has written in an article entitled THE JOHNS HOPKINS UNIVERSITY AND DIFFRACTION GRATINGS (Journal of the Optical Society of America, Vol. 50, p. 1148, 1960):

"Ultra-precision gratings are now being made by interferometric control of the motions of the ruling engine" (at MIT). Dr. Strong here uses "ultra-precision" in contrast to the term "precision" which he applies to gratings produced by mechanical engines.

In a paper published in JOSA, Vol. 50, p. 1045, 1960, Rank, Skorinko, Eastman, Saksena, McCubbin, and Wiggins write: "The detail displayed on our double-pass grating plates by far exceeds that of any published photographs of these lines available in the literature ..... After we had obtained our plates Harrison, Sturgis, Davis and Yamada (JOSA, Vol. 48, p. 287, 1958) announced their success in ruling 10-inch wide diffraction gratings of extremely high perfection. Observation of Professor Harrison's beautiful slides of his single-pass photographs made obvious the superior quality of his 10-inch gratings. We have held up the publication of our work until we have been able to procure such a grating.

"By making use of a Bausch & Lomb replica of a 10-inch Harrison grating of 300 lines/mm we have photographed λ 5461 in the 11th order, double pass, using the absorption technique previously described .....

"We had available a grating of 9.4 inches of sensibly perfect ruling after masking. Visual observation of λ 5461 in the 11th order single-pass showed the resolution to be extremely high .....

"It is difficult to estimate the resolving power achieved with the Harrison grating. The effective width as used double-pass was about 16 inches. From the performance in resolving λ 4358 central components a resolving power well in excess of 1 million is demonstrated ....."

Dr. Howard S. Coleman of Bausch & Lomb, Inc. has written us "We have now completed examination of the 5 test gratings of various kinds which you have submitted for our opinion as to quality. We find these gratings to be outstanding. Not only are two of the gratings of sizes larger than were previously available, but Rowland ghost intensities are lower than in any gratings we have examined before and satellite intensities have been in most cases reduced to new low levels. In order to make them more generally available to the scientific and technological community, we plan to engage in a development program designed to make possible the replication of such gratings."

LIMITATIONS OF PRESENT ENGINE

The basic limitation of the present engine is that its heavy blank carriage rolls on balls, and it is almost impossible to prevent vertical motions of the carriage of the order of 1 millionth of an inch, owing to the inevitable presence of dust particles. A sliding or wiping contact would be a great improvement. The balls had been introduced in Chicago in an effort to cut down sliding friction, but at present it appears impossible to obtain balls of the needed diameter which are within less than 1 millionth of an inch deviation from sphericity and absolute diameter. The geometry of the engine is such that any change in ball diameter produces an inevitable small and uncontrollable change in spacing.

Another limitation arises from vibrations which come in through the three engine pediments. A 1700 kw motor-generator set running nearby produces transients on starting and stopping which are sufficient to cause the engine to jump a fringe, and at times a very disagreeable 10-cycle component comes through the ground from this generator. Attempts have been made to improve its balance, but the residual vibrations are such that it is obvious that the ruling engine should be mounted on an anti-vibration base of several tons weight, arranged to cut out all frequencies above 6 cycles up. This would be impractical with the present engine, surrounded as it is by an oil bath, and is hardly feasible in view of the experimental nature of this project.

A serious limitation on our grating production, which has nothing to do with the engine is the difficulty of obtaining large optical blanks coated with adhering films of aluminum which have the necessary flatness to 1/10 wave over their entire surface. This is particularly true for echelle blanks in which the aluminum must be as much as 30 microns in thickness. This problem is now being worked on at Bausch & Lomb, at Jarrell-Ash Company, and at Perkin-Elmer Corporation, and should eventually be solved. It appears correct to say that as of now it is more difficult to get a good flat blank than it is to rule a true and ultra-precision grating on it.

NEW RULING ENGINE OF LARGER CAPACITY

In an attempt to overcome these difficulties it was decided to use the facilities of the project, plus others, to initiate the construction of a ruling engine of 10 x 18 inch capacity. Larger gratings are badly needed for the infrared region, and the astronomers and many others would have use for 18-inch gratings which could be used at high angles in the visible.

We decided to follow the experience we had gained in our ten years on the present 12-inch ruling engine, but in addition to strike out in new experimental directions. It would be useful if we could make the base of the new interferometrically controlled engine a standard commercial product, which could be purchased on the open market. A comparison of various precision measuring engines was made, and one manufactured by the Moore Special Tool Company of Bridgeport, Connecticut, was selected as furnishing a good beginning for our operations.

One of the Moore special measuring engines, guaranteed accurate to 30 millionths of an inch, was purchased and is now being modified to permit the ruling of blanks 10 inches wide and up to 20 inches long. It is hoped that our methods of interferometric control, using continuous motion of the blank, will serve to increase the precision of this engine from its 30 millionths of an inch to 3/10 of a millionth of an inch, or about 100-fold.

Preliminary tests with an interferometer on the precision of the screw of this engine and on the straightness of its ways show these to be excellent in ordinary mechanical terms, but to be subject to limitations arising from oil film thickness variations. Thus, the ways were found straight to ±2 millionths of an inch in one traverse of the carriage, and some time later were found to have a curvature of about 10 times this, due to changing oil film thickness. These effects could be adequately taken care of only by a constant correction device such as the interferometric servo-control furnishes.

In order to reduce the vibration problem, the new engine is being mounted on

a 5 ton slab of concrete suspended from spring mountings and recessed into the floor of the laboratory. Three large interferometers are being set up to control it, these controlling respectively translation, rotation about a vertical axis, and rotation about a horizontal axis. This last feature, which is not on our 12-inch engine, should further reduce the residual spacing variations. The use of a sliding carriage instead of one rolling on balls should make the correction problem very much simpler. Whereas, in the present engine corrections must be made within a fraction of a second, if they are to be adequate, it is expected that in the new engine variations from correct positioning will be slow and the servo mechanisms will thus have a lighter load.

An outstanding difficulty of the new engine will be the necessary weight of its moving parts, which will be of the order of several hundred pounds. Whether it will be possible to move such a heavy weight uniformly and slowly over a period of a week or more without elastic deformations remains to be seen, but circumstances seem to be such that such difficulties should be at a minimum in the new engine compared to any other previously built, because of our use of the principle of uniform motion of the blank during ruling. Stopping and starting such a heavy mass and controlling it to a fraction of a millionth of an inch would with present techniques be extremely difficult.

It should not be considered that because our gratings have been designated ultra-precision that they are as perfect as is needed. Gratings have always been called "perfect" by their makers, ever since the days of the first successful 6-inch gratings ruled by H. A. Rowland in 1883, devices of very low quality compared to the gratings of today. No grating ever ruled is a perfect optical instrument, and while those now available are almost adequate for the visible and near ultraviolet regions, their errors increase as the wavelength of the light used is shortened. Thus great improvements are needed, particularly for gratings used in the extreme ultraviolet. Also it is desirable to use gratings at still higher angles than 75° in autocollimation to increase dispersion.

PERSONNEL

This project has been under the direction of Dr. George R. Harrison, Professor of Physics and Dean of the School of Science at M.I.T. His aids under the contract, at various times, have been Dr. George W. Stroke, Neville Sturgis and Frank Denton, together with guest researchers and assistants as listed in the papers cited.

George R. Harrison
Project Director

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